

**Multi-Mode and Non-Standard Classical Cepheids
in the Magellanic System***I. Soszyński¹, A. Udalski¹, M.K. Szymański¹, R. Poleski^{1,2},
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Coventry, CV4 7AL, UK*Received***ABSTRACT**

We present a sample of the most interesting classical Cepheids selected from the OGLE collection of classical Cepheids in the Magellanic System. The main selection criterion for this sample was the presence of non-standard, unique pulsational properties.

The sample contains the first known double-mode Cepheid pulsating in the second- and third-overtone modes and a large number of objects with non-radial modes excited. We also found Cepheids revealing Blazhko-like light curve modulation, objects ceasing pulsations or showing atypical shapes of their light curves. Additionally, the status of several triple mode classical Cepheids is updated based on OGLE-IV photometry extending the time baseline to 15 years.

Key words: *Cepheids – Stars: oscillations – Magellanic Clouds***1. Introduction**

Classical Cepheids provide a unique astrophysical laboratory for studying stellar pulsations. The vast majority of these stars are single-periodic, radial, fundamental-mode (F) or first-overtone (1O) pulsators. A relatively small fraction of classical Cepheids have two consecutive radial modes simultaneously excited: either the fundamental and first-overtone modes (F/1O) or the two lowest-order overtones (1O/2O). This simple picture has been significantly modified in recent years,

*Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution for Science.

largely thanks to the publication by the Optical Gravitational Lensing Experiment (OGLE) long-term, high-quality light curves of a large number of Cepheids.

The zoo of observed pulsation modes and their combinations was extended by pure second-overtone pulsations (2O, Udalski *et al.* 1999), simultaneous oscillations in the first and third overtones (1O/3O, Soszyński *et al.* 2008a), and triple-mode pulsations in the fundamental, first, and second overtone modes (F/1O/2O) or in the first three overtones (1O/2O/3O, Moskalik *et al.* 2004, Soszyński *et al.* 2008a). Moreover, non-radial modes have been firmly detected in the OGLE first-overtone Cepheids (Moskalik and Kołaczowski 2008, Soszyński *et al.* 2008b, 2010). These modes manifest themselves in the form of additional, small-amplitude variability with periods which are equal to 0.60–0.65 of the dominant (first-overtone) pulsation periods. The latter objects provided new challenges for stellar pulsation theory (Dziembowski 2012, Smolec and Śniegowska, in preparation).

The OGLE long-term sky-variability survey has recently released a unique collection of classical Cepheids in the Magellanic System (Soszyński *et al.* 2015). This is the most complete and uniform sample of these stars, containing about 10 000 classical Cepheids from the wide area around the Magellanic Clouds and Magellanic Bridge. The millimagnitude accuracy and standard *VI*-bands of the OGLE photometry make this dataset very attractive in searching for and studying fine effects in pulsating classical Cepheids. The empirical constraints resulting from the OGLE collection data should shed new light on many aspects of stellar pulsations.

Here we present several examples of the most interesting non-standard classical Cepheids in the OGLE collection concentrating on those revealing unique pulsation schemes and other phenomena closely connected with stellar pulsations. We also update the status of several multi-mode classical Cepheids discovered by OGLE in earlier phases of the OGLE survey (Soszyński *et al.* 2008a). Thanks to additional photometric coverage collected during the OGLE-IV phase (2010–2015) and, thus, considerable extension of the observing time-span, it was possible to refine the pulsating properties of these objects.

2. Observations and Photometric Data

The photometry presented in this paper was collected during the third and fourth phases of the OGLE survey in the years 2001–2015. Since 2010, the 1.3-m Warsaw telescope with a 32-CCD detector mosaic camera covering 1.4 square degrees with a 0.26 arcsec/pixel scale was used. The Magellanic System Survey conducted during OGLE-IV covered ≈ 650 square degrees around the Magellanic Clouds including the Magellanic Bridge. A typical cadence of the main *I*-band variability survey was 2–4 days. Observations were supplemented with much less frequent *V*-band observations carried out to secure color information. The total number of *I*-band epochs varied from field to field in a range of 100 to over 750. In the *V*-band, from several to up to 260 epochs were collected. More information on

the technical details and observing strategy of the OGLE-IV survey can be found in Udalski *et al.* (2015).

Classical Cepheids were extracted from millions of variable stars with techniques described in Soszyński *et al.* (2015). The latest OGLE collection of classical Cepheids contains 9535 objects. Precise photometry and full characterization of each object is available from the OGLE Internet archive. The completeness of the sample is very high – well over 95%. Thus, with predicted small future updates, the OGLE collection of classical Cepheids provides the final census of these very important variables in the Magellanic System. For more details on the OGLE collection the reader is referred to Soszyński *et al.* (2015).

3. Multi-Mode Cepheids

The Petersen diagram (a plot of the ratio between two periods against the logarithm of the longer one) is the basic and very sensitive tool to diagnose multi-mode pulsating stars. In Fig. 1, we present the Petersen diagram for multi-periodic Cepheids in the Magellanic Clouds constructed using data from the OGLE collection of classical Cepheids in the Magellanic System (Soszyński *et al.* 2015). Blue and red symbols indicate the LMC and SMC variables, respectively. Double-mode radial pulsators are marked with filled circles, each triple-mode Cepheid is represented by three triangle symbols, other multi-periodic Cepheids are denoted by empty circles.

Double-mode F/1O Cepheids from both Clouds show a well-known separation in the Petersen diagram (Beaulieu *et al.* 1997), while 1O/2O variables mostly overlap. However, the largest sample of double-mode Cepheids reveals subtle details of their distribution in the Petersen diagram, namely the shortest period F/1O variables seem to have very similar period ratios in the LMC and SMC, while the shortest-period 1O/2O Cepheids split up in this diagram.

3.1. A New Type of Double-Mode Cepheids (2O/3O)

Among the newly identified double-mode Cepheids in the OGLE collection one case deserves special attention. We found a unique double-mode pulsator, OGLE-LMC-CEP-3987, which oscillates simultaneously in the second and third overtones. To our knowledge this is the first such classical Cepheid known.

In Fig. 2, we plot the two components of its light curve, separated with the Fourier technique. The star has a proper position in the appropriate sequences corresponding to second- or third-overtone Cepheids in the period–luminosity diagram plotted for the LMC Cepheids (Fig. 3). Its light amplitudes associated with both modes are quite large and the ratio of the periods agrees with the corresponding modes in triple-mode Cepheids (Fig. 1). Thus, the identification of modes in OGLE-LMC-CEP-3987 seems to be firm, despite the fact that we did not detect any combination frequencies in the power spectrum.

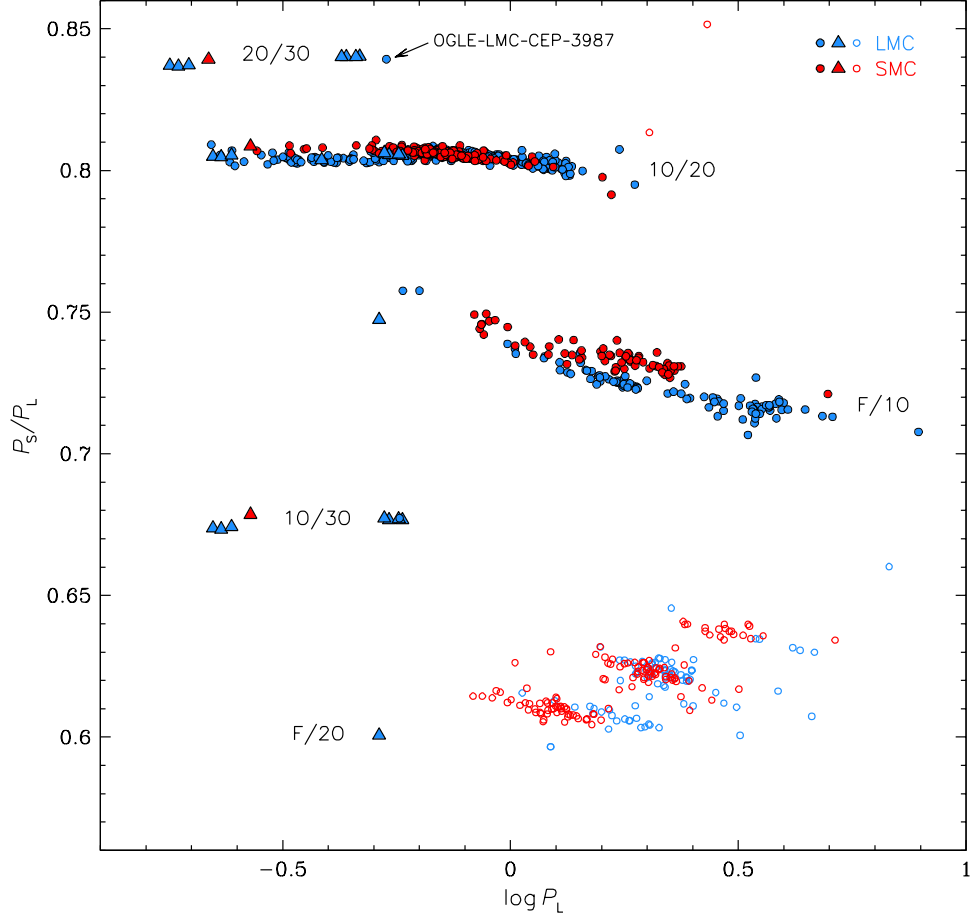


Fig. 1. Petersen diagram for multi-mode classical Cepheids in the Magellanic Clouds. Filled circles represent double-mode Cepheids, triangles mark triple-mode Cepheids (three points per star) and empty circles show other selected stars with significant secondary periods. Blue and red symbols represent variables in the LMC and SMC, respectively.

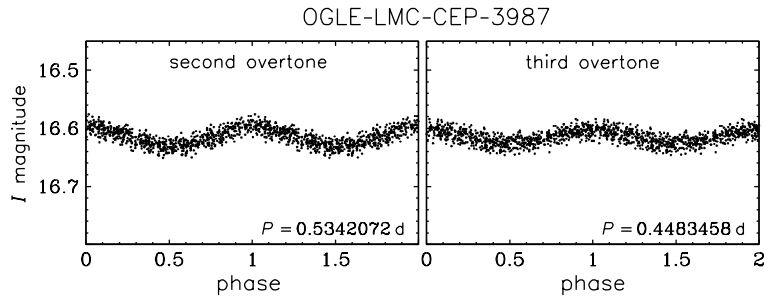


Fig. 2. Light curve of a double-mode Cepheid OGLE-LMC-CEP-3987 pulsating in the second and third overtones. Both modes are separated with the Fourier technique. *Left* and *right panels* present the light curves of the second-overtone and the third-overtone modes, respectively.

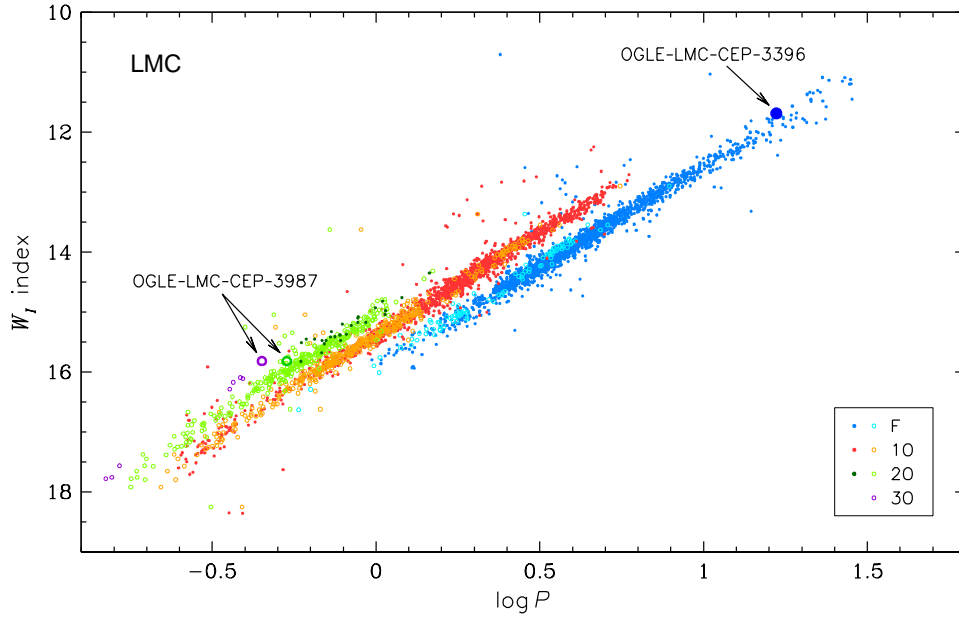


Fig. 3. Period–Wesenheit index (where $W_I = I - 1.55(V - I)$) diagram for classical Cepheids in the LMC. Blue, red, and dark-green solid circles mark F, 1O, and 2O single-mode Cepheids, respectively. Cyan, orange, light-green and violet empty circles represent, respectively, F, 1O, 2O, and 3O modes in multi-mode Cepheids. Arrows show the position of the double-mode 2O/3O Cepheid OGLE-LMC-CEP-3987 and the fundamental-mode Cepheid with a sinusoidal light curve OGLE-LMC-CEP-3396.

3.2. Status of Known 1O/3O Double-Mode and Triple-Mode Cepheids

Soszyński *et al.* (2008a) discovered two double-mode classical Cepheids pulsating simultaneously in the first and third overtones (1O/3O). The periods and period ratios of these two stars are practically the same as in their triple-mode 1O/2O/3O counterparts. Based on that, it was suggested that in fact double-mode 1O/3O and triple-mode 1O/2O/3O Cepheids belong to the same class of pulsating stars. With the OGLE-IV photometry we can confirm this suggestion, since at least one of the 1O/3O Cepheid indeed became a triple-mode Cepheid. In OGLE-LMC-CEP-0691 we found a weak but statistically significant signal (with full amplitude of 0.009 mag) corresponding to the second overtone. In the OGLE-III light curve of the same star such a signal is undetectable (Fig. 4). In the other 1O/3O Cepheid (OGLE-LMC-CEP-1106) we still cannot detect a clear signal of the second-overtone oscillation. We suspect it may be hidden below the OGLE detection threshold.

On the other hand, one of the triple-mode F/1O/2O Cepheids from the OGLE-III release (namely OGLE-LMC-CEP-0857) switched to a double-mode 1O/2O pulsations. Very weak signal of the fundamental mode (0.006 mag) detectable in the OGLE-III light curve became invisible in the OGLE-IV dataset. With the OGLE-IV photometry we also do not confirm the existence of the fundamental

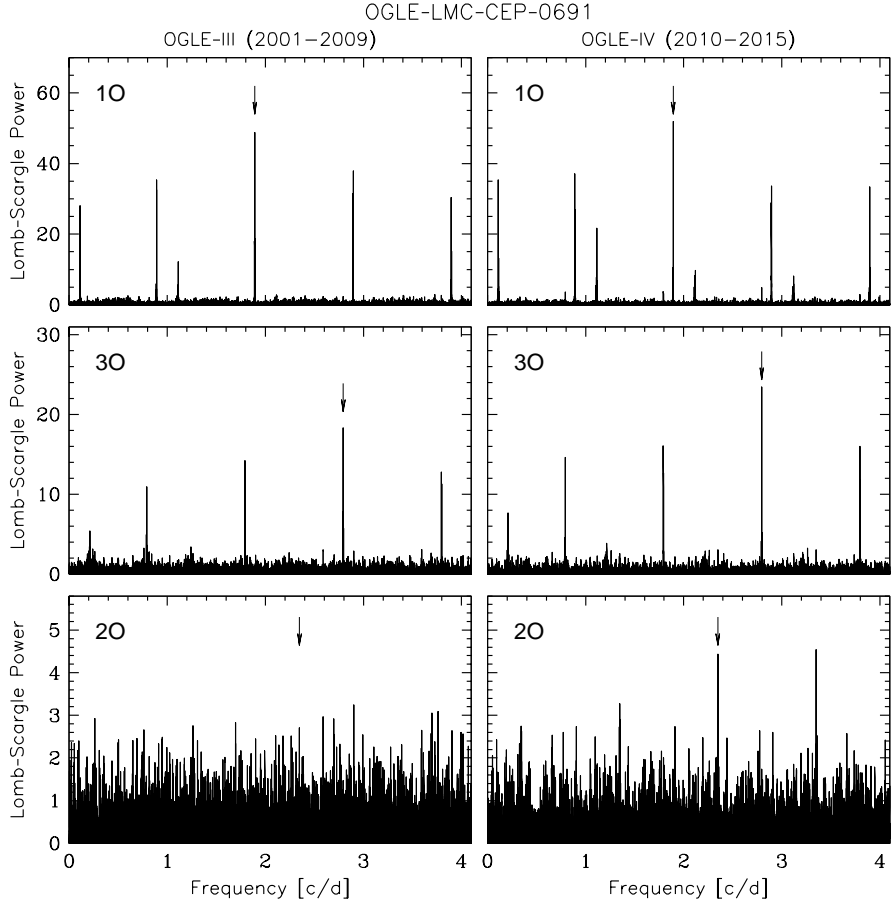


Fig. 4. Lomb-Scargle periodograms of OGLE-LMC-CEP-0691 – a classical Cepheid that switched from a double-mode 10/30 to a triple-mode 10/20/30 pulsator. *Left panels* were obtained based on the observations collected during the OGLE-III survey (2001–2009), while the *right panels* display power spectra of the same star monitored by the OGLE-IV project (2010–2015). *Upper panels* show periodograms obtained for the original light curves with the first-overtone mode indicated by the arrows. *Middle panels* display power spectra after prewhitening with the dominant (first-overtone) mode. The arrows show the frequencies of the third overtone mode. *Lower panels* show the power spectra after prewhitening with the first and the third overtone modes. Note that the second-overtone frequency (indicated by the arrow) was hidden in noise during the OGLE-III survey.

mode in two candidate triple-mode F/10/20 Cepheids in the SMC reported in the OGLE-III Cepheid sample: OGLE-SMC-CEP-1077 and OGLE-SMC-CEP-1350. Soszyński *et al.* (2010) indicated that the potential fundamental-mode periods in both stars should be treated as uncertain detections, since amplitudes of these variations were at the detection limit of the OGLE-III photometry. New more precise OGLE-IV observations prove that the fundamental-mode periods reported by Soszyński *et al.* (2010) were not real. Therefore, we presently moved both objects to the group of double-mode 10/20 Cepheids. Furthermore, we reclassi-

fied two double-mode Cepheids in the LMC (OGLE-LMC-CEP-3369 and OGLE-LMC-CEP-3374) as triple-mode pulsators and found one additional triple-mode Cepheid – OGLE-LMC-CEP-3878. Summarizing, OGLE collection now contains nine triple-mode Cepheids in the Magellanic Clouds: one pulsating simultaneously in the fundamental mode, first, and second overtones (F/1O/2O) and eight with the first three overtones (1O/2O/3O) excited. Tables 1 and 2 give periods and amplitudes of the individual modes of triple-mode Cepheids in the OGLE collection. It is worth mentioning that 1O/2O/3O Cepheids in the Magellanic Clouds clearly form two groups: the shorter-period one (with $P_{1O} < 0.27$ d) and the longer-period one (with $P_{1O} > 0.52$ d).

Table 1

Triple-Mode F/1O/2O Cepheids in the Magellanic Clouds

Identifier	P_F [days]	A_F [mag]	P_{1O} [days]	A_{1O} [mag]	P_{2O} [days]	A_{2O} [mag]
OGLE-LMC-CEP-1378	0.5150335	0.041	0.3849422	0.218	0.3093878	0.046

Table 2

Triple-Mode 1O/2O/3O Cepheids in the Magellanic Clouds

Identifier	P_{1O} [days]	A_{1O} [mag]	P_{2O} [days]	A_{2O} [mag]	P_{3O} [days]	A_{3O} [mag]
OGLE-LMC-CEP-0691	0.5283428	0.108	0.4259550	0.009	0.3578421	0.027
OGLE-LMC-CEP-1847	0.5795056	0.247	0.4666566	0.028	0.3921303	0.037
OGLE-LMC-CEP-2147	0.5412814	0.265	0.4360338	0.044	0.3662933	0.070
OGLE-LMC-CEP-3025	0.5687003	0.271	0.4582428	0.027	0.3849952	0.030
OGLE-LMC-CEP-3369	0.2318730	0.080	0.1866128	0.070	0.1561395	0.081
OGLE-LMC-CEP-3374	0.2222560	0.203	0.1788862	0.072	0.1497371	0.066
OGLE-LMC-CEP-3878	0.2443469	0.238	0.1967768	0.041	0.1647337	0.080
OGLE-SMC-CEP-3867	0.2688496	0.289	0.2173832	0.044	0.1824242	0.087

3.3. Non-Radial Modes in Cepheids

Some first-overtone Cepheids show small-amplitude secondary periodicities 0.60–0.65 times shorter than the primary periods. First such stars were detected by Moskalik and Kołaczowski (2008) in the OGLE database. Soszyński *et al.* (2008b, 2010) significantly increased the sample of such stars and showed that these “0.6 Cepheids” form two (in the LMC) or three (in the SMC) sequences in the Petersen diagram. The secondary periods in these stars are likely caused by non-radial modes, but it is still unclear which modes are responsible for this phenomenon (Dziembowski 2012).

In Fig. 1, we plot with open circles the “0.6 Cepheids” detected among our overtone pulsators. In the preliminary search, we found 82 and 127 such stars in the LMC and SMC, respectively, but more sophisticated analysis of the OGLE light curves may reveal additional objects of that type. The vast majority of our “0.6 Cepheids” pulsate in a single radial (first-overtone) mode, but we also found additional periods in two double-mode 1O/2O Cepheids (OGLE-LMC-CEP-4482, OGLE-SMC-CEP-2770) and in one F/1O Cepheid (OGLE-SMC-CEP-1497).

Our investigation reveals that the “0.6 Cepheids” in the LMC follow three sequences in the Petersen diagram, like their counterparts in the SMC, although the third sequence (the highest-period-ratio one) is populated only by a few objects. The distributions of periods of the “0.6 Cepheids” are clearly different in both Clouds. In particular, in the first sequence (the lowest-period-ratio one), the LMC Cepheids have on average longer periods than in the SMC.

4. Non-Standard Cepheids

In this section we present several potentially interesting classical Cepheids in our collection with unusual pulsating properties.

4.1. *Blazhko-Like Effect in Classical Cepheids*

The long time span of the OGLE light curves offers the opportunity to study non-stationary properties of pulsating stars. As an example, in Fig. 5 we present light curves of three classical Cepheids exhibiting significant amplitude and phase modulations, a phenomenon analogous to the Blazhko effect in RR Lyr type stars. Such a behavior is common in RR Lyr stars, while in classical Cepheids it was observed only in double-mode 1O/2O pulsators (Moskalik and Kołaczowski 2009) and in a second-overtone Cepheid V473 Lyr (Molnár and Szabados, 2014). Our collection contains more such cases, not only in double-mode pulsators. The upper panel of Fig. 5 shows the light curve of OGLE-LMC-CEP-1546 – a single-mode first-overtone pulsator.

4.2. *Ceasing Pulsations*

OGLE-SMC-CEP-3043 is another extraordinary object found in our collection. It is a first-overtone Cepheid observed by OGLE from the beginning of the third phase of the project. During the 15-year-long monitoring this star experienced a monotonic decrease of the pulsation amplitude and currently its amplitude is below the detection limit of the OGLE survey. In Fig. 6, we plot light curves of OGLE-SMC-CEP-3043 in three observing seasons (in 2001, 2008 and 2013–2014). The lower panel of Fig. 6 displays changes of the amplitude through the years. Our collection contains two more candidates for Cepheids – OGLE-SMC-CEP-1133 and OGLE-SMC-CEP-2081 (both of the second-overtone modes) – that apparently stopped their pulsations.

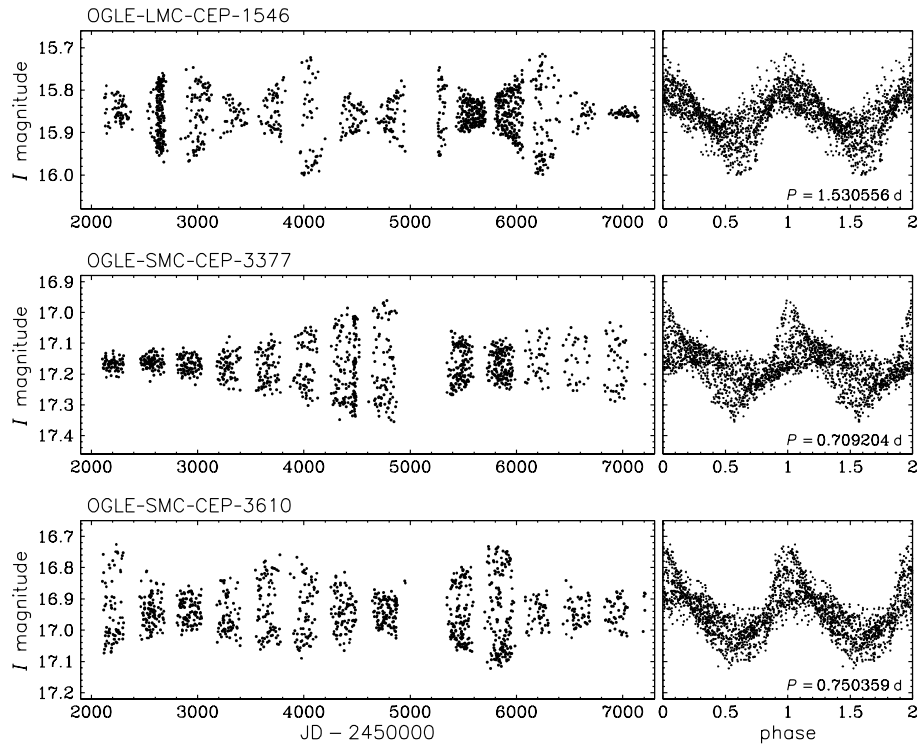


Fig. 5. Light curves of three classical Cepheids with a Blazhko-like effect. *Left panels* present unfolded light curves collected in the years 2001–2015. *Right panels* show the same light curves folded with the pulsation periods.

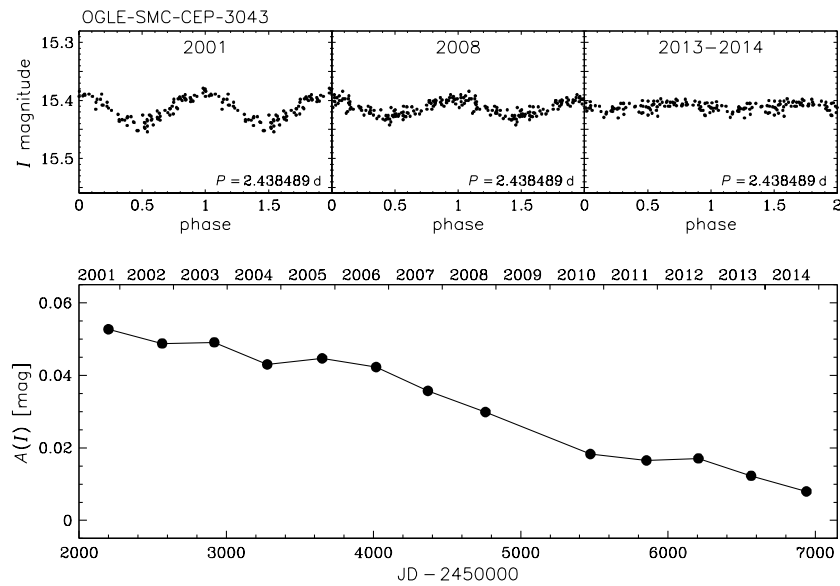


Fig. 6. OGLE-SMC-CEP-3043 – a first-overtone Cepheid that stopped its pulsations. *Upper panels* show seasonal light curves of OGLE-SMC-CEP-3043 in three time ranges: 2001, 2008 and 2013–2014. *Lower panel* presents the changes of the pulsation amplitude through the years.

4.3. Unusual Light Curve Shape

OGLE-LMC-CEP-3396 was discovered by Ulaczyk *et al.* (2013) using photometric data collected during the OGLE-III Shallow Survey. This object reveals a nearly sinusoidal light curve with a period of 16.68 d (Fig. 7) what is unusual for fundamental-mode Cepheids with similar period (*cf.* Fig. 1 in Soszyński *et al.* 2008b). Nevertheless, despite the unusual shape of its light curve, we confirm the classification of Ulaczyk *et al.* (2013). OGLE-LMC-CEP-3396 lies in the PL relation of the fundamental-mode classical Cepheids in the LMC (Fig. 1), the ratio of amplitudes in the V - and I -bands ($A(V)/A(I) = 1.6$) has a typical value for classical Cepheids, and the most persuasive indication of the pulsations in this star is a characteristic for Cepheids phase shift between the V - and I -band light curves (Fig. 7) which excludes the possibility that this is an ellipsoidal variable. This example illustrates potential difficulties in the classification of variable stars in our Galaxy, when the distance and reddening to the stars are not *a priori* known (see also Pietrukowicz *et al.* 2015).

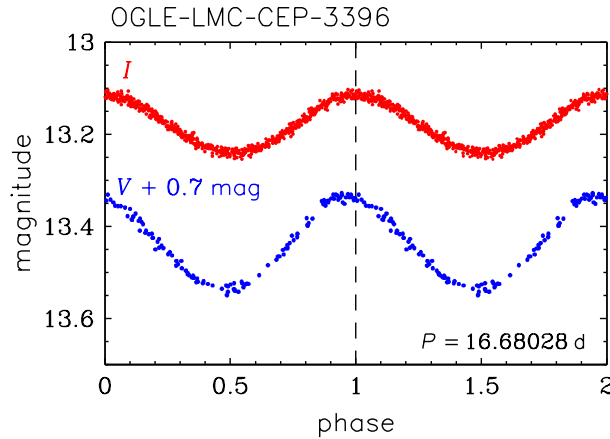


Fig. 7. I -band (red points) and V -band (blue points) of a fundamental-mode classical Cepheid OGLE-LMC-CEP-3396. Note the characteristic amplitude ratio and the phase shift between the curves.

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